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UNITED STATES
PATENT APPLICATION

for a new and useful invention entitled

**Switched-Mode Power Amplifier Using
Lumped Element Impedance Inverter for Parallel Combining**

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SWITCHED-MODE POWER AMPLIFIER USING LUMPED ELEMENT IMPEDANCE INVERTER FOR PARALLEL COMBINING

Field of the Invention

[00001] The invention relates to circuitry for radio frequency (i.e. "RF" or "wireless") transmitters and, in particular, to a switched-mode power amplifier design and configuration for parallel connection with one or more like amplifiers for combining of the signals output therefrom.

Background of the Invention

[00002] Typically, power combiners are used in RF transmitters to combine the output signals of parallel power amplifiers into one high power RF output signal for wireless transmission. In these known transmitter structures the signals are first amplified by the power amplifiers and then they are combined by a separate power combiner to produce a combined amplified signal for transmission. Depending upon the circuit architecture and signal format used, however, it becomes necessary to make trade-offs between reducing power losses and achieving isolation between input signals of the combiner.

[00003] The need for efficiency is a particularly important design factor for the highly integrated requirements of transceivers used for wireless local area networks (LANs) and employing modulation formats such as OFDM (Orthogonal Frequency Division Multiplex). Moreover, the assignee of this invention and application has developed signal modulation methods, using OFDM signal format, whereby information signals are deconstructed into independent component signals, these independent signals being more efficiently processed and modulated than the original information signals from which they derive, and then the independent signals are up-converted, amplified and combined prior to transmission. Use of such independent modulated signals presents additional challenges to achieving efficiency at the amplification/combination stages of the

transmitter, however, because the conventional model of amplification followed by combining, using known power amplifiers and combiners, is subject to inherent loss and isolation limitations.

[00004] The Chireix-type power amplifier, known to persons skilled in the art, represents one of the LINC (Linear amplification with Nonlinear Components) architectures and uses linear, saturated, or switch-mode amplifiers to provide amplification for signals having amplitude as well as phase modulation. It operates by adjusting the phase applied to two amplifiers, and combining the outputs through a combiner to reintroduce the amplitude modulation. An appropriate combiner for the Chireix architecture not only reinserts the amplitude modulation to the signal, it also provides a dynamic adjustment of the load impedance presented to each amplifier (out-phasing). This out-phasing adjustment of the load impedances is such that the DC current through each active device decreases as the combined output amplitude decreases, thereby maintaining high efficiency.

[00005] Appropriate combiners for a Chireix-type amplifier do not provide any isolation between the outputs of the two amplifiers. One example of this is a "pseudo" balanced magnetic transformer (i.e. having no center tap to ground connection) connecting the individual amplifier outputs to the two terminals, Input 1 and Input 2, of the input winding 100, as shown in the prior art illustration of Figure 1. Here the magnetic transformer effectively combines, in series, in the output winding 200, the signals from the individual amplifiers and, for efficiency, the outputs of the individual amplifiers must be low impedance voltage sources. However, it will be understood by the skilled reader that such use of a magnetic transformer inherently introduces significant loss due to the limited Q achievable for the coils on a semiconductor substrate.

[00006] Alternatively, the amplifiers in a Chireix-type amplifier architecture

can, instead, be connected in parallel if an appropriate impedance transformation is incorporated, that is, if the low impedance voltage source outputs (i.e. the individual amplifier outputs) are transformed into high output impedance current sources. With such a transformation, the high output impedance current source outputs can be connected in parallel, thereby avoiding the need for a magnetic transformer. As known by persons skilled in the art, this transformation can be achieved with a quarter-wave length transmission line, also referred to as an impedance inverter, as shown in the prior art illustration of Figure 2, wherein the characteristic impedance (Z_0) of the two quarter-wave length transmission lines is set to match the output impedance of the amplifier stage to the desired load impedance.

[00007] Instead of using such a quarter-wave length transmission line, the impedance inversion (transformation) can also be achieved using a lumped element equivalent circuit, as known to persons skilled in the art. Such a lumped element equivalent for broadband may consist of a series inductor, L , and two shunt negative inductances of equal absolute value, $-L$, as shown by the prior art illustration of Figure 3A. Here, a load impedance Z_L is transformed into an input impedance $Z_{in} = \omega^2 L^2 / Z_L$. Alternatively, the lumped element equivalent circuit shown by the prior art illustration of Figure 3B could be used for such impedance transformation. As will be appreciated by the skilled reader, these negative inductances, $-L$, can be realized, for a limited bandwidth (spot frequency) application, with the use of shunt capacitances; however, this is not applicable for a practical Class F amplifier for which such impedance inversion is needed at each of the first, second and third harmonics. Consequently, the realization of such a transformation for Class F amplifier circuits presents an obstacle for the practical design and implementation of such a circuit.

[00008] As illustrated by Figure 4, the known switched-mode Class F amplifier provides a good approximation to a voltage square-wave across the

output terminals of an active device 300 (the active device being a transistor in the usual case connected at its source, through a bias inductor 307, to a voltage rail 305) by “shorting” all even-harmonic voltages and “supporting” all odd-harmonic voltages. As a result, the voltage waveform across the output terminals of the active device 300 contains only odd-harmonic components. In addition, this sorting of odd- and even-harmonics results in a current passing through the output terminals of the active device 300 that contains the fundamental, and only even-harmonic components. Such “shorting” and “supporting” of the even and odd harmonics, respectively, is conveniently achieved, up to the third harmonic, with a series resonant circuit 310, 320 tuned to the second harmonic connected across the active device's output terminals, and a parallel resonant circuit 330 and 340 at the third harmonic connected between the output terminal of the active device 300 and the load 350. In operation, the series resonator 310,320 effectively shorts the second harmonic of the input signal (V_{in}) and supports the third harmonic of the input signal, while the parallel resonator 330,340 effectively blocks the third harmonic of the input signal from the load 350. Since each such harmonic component contains only a voltage component or a current component, the active device 300 does not absorb power other than at the fundamental frequency. Accordingly, as a result of the second and third harmonic resonators, only (approximately) the fundamental frequency signal reaches the load 350 at output terminal 351.

[00009] From a practical perspective, it is known that using such resonator circuits to process the input signal only up to its third harmonic components can provide a power-added efficiency of up to about 90%. However, it is also known that this Class F amplifier circuit architecture, where used at high frequencies, presents a design problem relating to the resonator circuits in that a source-drain (emitter-collector) parasitic capacitance results across the active device and causes the resonance values of these resonators to detune. In turn, this means that some level of amplitude for all harmonics of the voltage and current

will exist, in practice, at such high frequencies.

[00010] By reason of the foregoing limitations, for a Class F, Chirix-type amplifier architecture there exists a need for new and efficient means to achieve power amplification and combining of modulated signals in transmitters.

Summary of the Invention

[00011] In accordance with the invention, there is provided a switched-mode Class F power amplifier configured for parallel connection with at least one other like amplifier for combining signals output from such parallel connected amplifiers. An input component comprises at least one active device configured to be alternately switched by a signal (i.e. an analog phase modulated signal) input thereto to present an amplified signal corresponding to the input signal, the amplified signal constituting a low output impedance voltage source. A lumped element impedance inverter is provided between the input component and an output resonator component, the impedance inverter being configured for transforming the low output impedance voltage source so as to constitute a high output impedance current source configured for the parallel connection. Negative reactive component values required by the impedance inverter are eliminated and effectively provided by incorporating those negative values into pre-selected reactive components of the input and output components.

[00012] Optionally, a source-drain parasitic capacitance across the active device is also eliminated by one or more pre-selected reactive components of the input component, with the value(s) of the pre-selected reactive components being pre-determined to effectively compensate for the parasitic capacitance.

[00013] In accordance with another aspect of the invention a plurality of the foregoing amplifiers are connected in parallel for combining signals output

from the amplifiers wherein an input component is provided for each of the plurality of amplifiers. A common output resonator component is provided (common to all of the plurality of amplifiers) and a lumped element impedance inverter for each of the plurality of amplifiers between the input component and output component. As for the single amplifier, the negative reactive component values required by each impedance inverter is eliminated and effectively provided by incorporating their values into pre-selected reactive components of the input and output components.

[00014] In accordance with a further aspect of the invention there is provided a method for amplifying an input signal to produce an output signal configured for parallel connection with at least one other like output signal for combining the output signals within a Chireix circuit architecture. The input signal is amplified by means of at least one active device configured to be alternately switched by the input signal and an amplified signal corresponding to the input signal is presented, the amplified signal constituting a low output impedance voltage source. A second harmonic resonator configured for shorting a second harmonic signal of said input signal is provided across the active device. The low output impedance voltage source is transformed to constitute a high output impedance current source by means of a lumped element impedance inverter, the high output impedance current source being configured for the parallel connection. A third harmonic resonator blocks a third harmonic signal of the input signal from a load connected to the output signal. Negative reactive component values required by the impedance inverter are eliminated and effectively provided by incorporating those negative values into pre-selected adjacent reactive components of the resonators.

Brief Description of the Drawings

[00015] An exemplary preferred embodiment of the invention is described in detail below with reference to the following drawings in which like references

refer to like elements throughout:

[00016] Figure 1 illustrates a prior art pseudo balanced, transformer (i.e. not having a centre-tap-to-ground connection) for series-combining the output signals (Input 1 and Input 2) of a switched-mode power amplifier;

[00017] Figure 2 illustrates a quarter-wavelength ($\lambda/4$) transmission line (impedance inverter), useful for transforming a high output impedance to a low output impedance, as known by persons skilled in the art;

[00018] Figures 3A and 3B illustrate two different, alternate lumped element circuit equivalents to the foregoing quarter-wavelength transmission line of Figure 2;

[00019] Figure 4 illustrates a conventional Class F switched-mode power amplifier circuit;

[00020] Figure 5 illustrates a Class F switched-mode power amplifier circuit according to that of Figure 4 but with the addition of an impedance inverter, per that of Figure 3A, connected to the output terminal of the amplifier before the load;

[00021] Figure 6 illustrates a modified Class F amplifier circuit over that of Figure 5, which includes the impedance inverter (transformer) of Figure 5 but replaces the parallel third-harmonic-tuned resonator circuit of Figure 5, with a series third-harmonic-tuned resonator circuit connected across the output terminal of the amplifier to ground;

[00022] Figure 7 illustrates a further modified Class F amplifier over that of Figure 6, in accordance with the present invention, in parallel connection with a

like amplifier according to the invention, wherein the left-most negative inductor (-L) of the impedance inverter (transformer) of Figure 6 is incorporated into the series second-harmonic-tuned resonator circuit of Figure 6 to produce the modified series second-harmonic-tuned resonator circuit shown in this figure and the right-most negative inductor (-L) of the impedance inverter (transformer) of Figure 6 is incorporated into the series third-harmonic-tuned resonator circuit of Figure 6 to produce the modified series third-harmonic-tuned resonator circuit shown in this figure; and,

[00023] Figure 8 illustrates modified parallel-connected circuit of Class F amplifiers configured in accordance with the invention, over that of Figure 7, in which the output third harmonic resonator components are replaced by one equivalent output resonator component common to both amplifiers.

Detailed Description of the Illustrated Embodiment

[00024] Surprisingly, the inventor has invented a Class F amplifier configured for parallel connection with at least one other like amplifier, for combining the outputs of such parallel connected amplifiers in a Chireix circuit architecture, which overcomes or avoids the disadvantages associated with the foregoing prior art transformer couplings used for combining amplifier outputs and impedance inverters in the form of quarter-wavelength transmission lines or lumped element equivalents thereto having negative reactive components.

[00025] As illustrated by Figure 5, the present invention is achieved by first transforming, by means of an impedance inverter 335 (consisting of series positive inductor 250 and shunt negative inductors 260, 270), the output of a Class F amplifier (i.e. at terminal 333) from that of a low impedance voltage source to a high impedance current source so that such output-transformed amplifier may be connected in parallel with another like amplifier configuration to combine the outputs of the two amplifiers. Then, as illustrated by Figure 6, the

parallel third harmonic resonator 330, 340 is transformed through that impedance inverter 335 into a series third harmonic resonator 360, 370 (i.e. the parallel resonator 330,340 is replaced by a series resonator 360, 370 across the output terminal 351 and ground). Then, as illustrated by Figure 7 (which shows two such amplifier circuits 500, 501, each configured in accordance with the present invention and connected in parallel to present an output signal at terminal 550 representing an amplification and combination of input signals Vin1 and Vin2) the negative impedances 260, 270 are eliminated by incorporating those negative impedance values (effects) into the values of pre-selected existing reactive components adjacent to them.

[00026] Specifically, as shown by Figure 7, the negative impedance 260 is incorporated into the series second harmonic resonator 310,320 to form a modified series second harmonic resonator 310a, 320a in the example shown. Alternatively, if the source bias voltage 305 is stable, that negative impedance could be incorporated into the source bias inductor 307. Also as illustrated by Figure 7, the negative impedance 270 is incorporated into the series third harmonic resonator 360, 370 in the example shown to form a modified series third harmonic resonator 360a,370a.

[00027] Further, since this modified third harmonic resonator circuit 360a,370a of the amplifier 500 is in parallel connection with the corresponding resonator circuit 360a,370a of the parallel-connected like amplifier 501, these resonator circuits may be replaced by one equivalent resonator circuit 460a, 470a, as shown by Figure 8.

[00028] Moreover, the inventor has also advantageously eliminated the aforementioned source-drain parasitic capacitance of the Class F amplifier which occurs at high frequencies, by compensating for its presence in the pre-selection of the modified values of the components 310a,320a of the second

harmonic resonator.

[00029] It has also been determined by the assignee of this invention that the positive inductance 250 of the impedance inverter can be realized as a wire-bond in a semiconductor product implementation of this circuit, whereby the actual Chireix (parallel) signal combining takes place off die at the package pin. The means and method of performing such a wire-bond realization is described in detail in a co-pending application assigned to the same assignee as this application, entitled "Integrated Circuit Incorporating Wire Bond Inductance" which was filed on 30 June, 2003.

[00030] The individual electronic and processing functions utilised in the foregoing described embodiment are, individually, well understood by those skilled in the art. Appropriate values to be pre-selected for the surrounding reactive components, for given signal frequencies, to incorporate the negative reactive values of the impedance inverter in accordance with the invention, can be readily determined, as needed, by such skilled persons. It is to be understood by the skilled reader that a variety of other implementations of the invention, apart from the specific embodiment illustrated herein, may be devised for substitution. The claimed invention herein is intended to encompass all such alternative implementations, substitutions and equivalents. Persons skilled in the field of electronic and communication design will be readily able to apply the present invention to an appropriate implementation for a given application.

[00031] Consequently, it is to be understood that the particular embodiments shown and described herein by way of illustration are not intended to limit the scope of the invention claimed by the inventors/assignee which is defined by the appended claims.